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Outlook of Carbon Capture Technology and Challenges

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Abstract

The greenhouse gases emissions produced by industry and power plants are the cause of global warming. Carbon Capture and Storage (CCS) technology, which can capture up to 90% of the waste carbon dioxide (CO2) produced from these plants, is the best approach for reducing the impact of fossil fuel emissions to climate change and global warming.

This paper presents an overview of the current technologies for Carbon Capture and Storage (CCS). The main capturing technologies including post-combustion, pre-combustion, and oxy – combustion are reviewed and compared. The various challenges associated with transportation and storage of carbon dioxide (CO_2) are also presented. Furthermore, recent advancements of CCS technology are discussed to highlight the latest progress made by the research community in developing cheaper carbon capture and storage systems such as solvents, sorbents, membranes and thin films for gas separations. Finally, possible research and development approach for CCS are reported to help fast track the commercialization of this technology.

Keywords: Carbon capture and Storage (CCS), Carbon dioxide, power plant, gasification

1. Introduction

Climate change is one of the major concerns for most research centers and governmental institutions around the world. It is caused by the high amounts of carbon dioxide (CO_2) in the atmosphere. Currently, most countries around the world still rely heavily on fossil commodities, which release significant amounts of CO_2, for power generation where almost 85% of power generated across the globe is from fossil fuel. A drastic substitution of the traditional power plant with alternative clean energy generation mediums, which produce no CO_2, is virtually impossible in the near future. Therefore Carbon Capture and Storage (CCS) technology has received increased attention by research community in the recent years. CCS technology helps in reducing the CO_2 and other greenhouse gases in the atmosphere that lead to depletion of the ozone layer and climate change. It is expected that the next few years will see carbon capture and storage as one of the cheapest methods for reducing greenhouse emissions [3, 4]. The main steps for implementing CCS in any power plant are presented in Fig. 1.

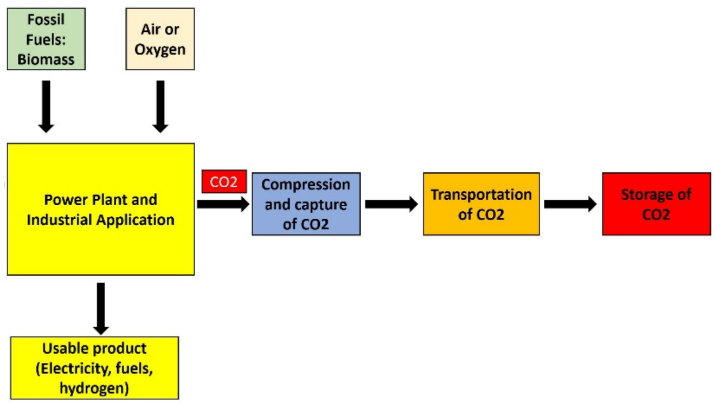

Fig. 1: Steps for carbon capture in a power plant and industrial application [1].

The CCS process starts with capturing the carbon dioxide generated by the biomass or fossil commodities. The carbon dioxide then undergoes a compression process to form a dense fluid that aids in easy transportation and storage of the CO_2. The dense fluid is transported via pipelines and then injected in an underground storage facility.

The current CCS technologies are generally very expensive and significant developments are needed to develop a more affordable CCS technology. Thus, the aim of this paper is to review the main CCS technologies and to explore the recent efforts made by the scientific community to come out with a new approach that can reduce the overall cost of this vital technology [5].

2. CO_2 capturing technologies

Significant amounts of CO_2 are produced during the combustion of natural gas and coal in power plants. These amounts are either directed towards the atmosphere or used in manufacturing plants to produce other commodities as in food processing industry [7]. However, only a small portion of the generated CO_2 is recycled by the manufacturing industry and most of the carbon dioxide eventually ends up in the atmosphere [5].

Several strategies for the capture of CO_2 from gaseous mixtures have been developed and utilized in the industry. Fig. 2 depicts the recent technologies used for CO_2 capture. The type of technology depends on the purity and conditions of the gas such as temperature, pressure and the concentration of the CO_2 [6]. CO_2 capture systems help in the elimination of impurities from the carbon dioxide during natural gas treatment and the generation of hydrogen, ammonia and other chemicals for industrial purposes.

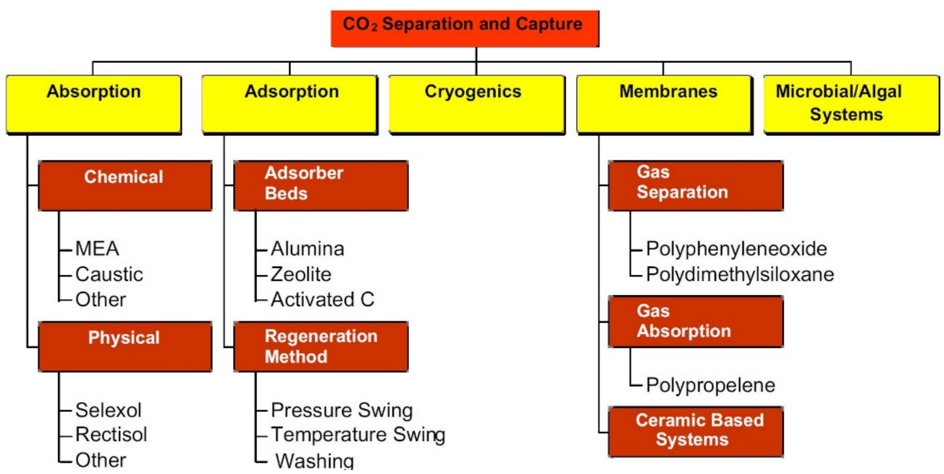

Fig. 2: Various technologies used in carbon capture and storage [5].

The overall objective for all CCS technologies is to generate carbon dioxide that can be stored in a geological formation. To materialize this, carbon dioxide must be compressed to a liquid state in order to be transported easily through pipelines and eventually pumped into a geological formation. The carbon compression stage can thus be considered as part of the carbon capture and storage system [9, 10]. Today, the technologies utilized for CCS are grouped as pre – combustion or post – combustion systems. These technologies are named depending on the timing when the carbon is eliminated that is prior or after the fossil fuel combustion [8]. There is another CCS technology, known as the oxyfuel or oxy – combustion, which is still under developmental stages and it requires sometime before it becomes commercially acceptable. The technology used by power plants is similar to that used by some industrial activities devoid of burning.

2.1 Pre – combustion approach

This technology employs the sequestration of CO_2 from fossil commodities or biomass fuel prior to the burning process being started [11]. This technology can further be explained as a reaction between fuel and oxygen or air or steam to generate a synthetic gas (fuel gas), carbon monoxide and hydrogen. A pure hydrogen fuel stream is obtained after the removal of carbon dioxide [12]. By means of integrated gasification, carbon dioxide can be obtained. The technology is also applicable to power plants that uses natural gas and combined cycle power generation [13,14]. Fig. 3 shows a diagram of carbon dioxide capture using the pre combustion technology approach. Table 1 also capture recent studies conducted in this field.

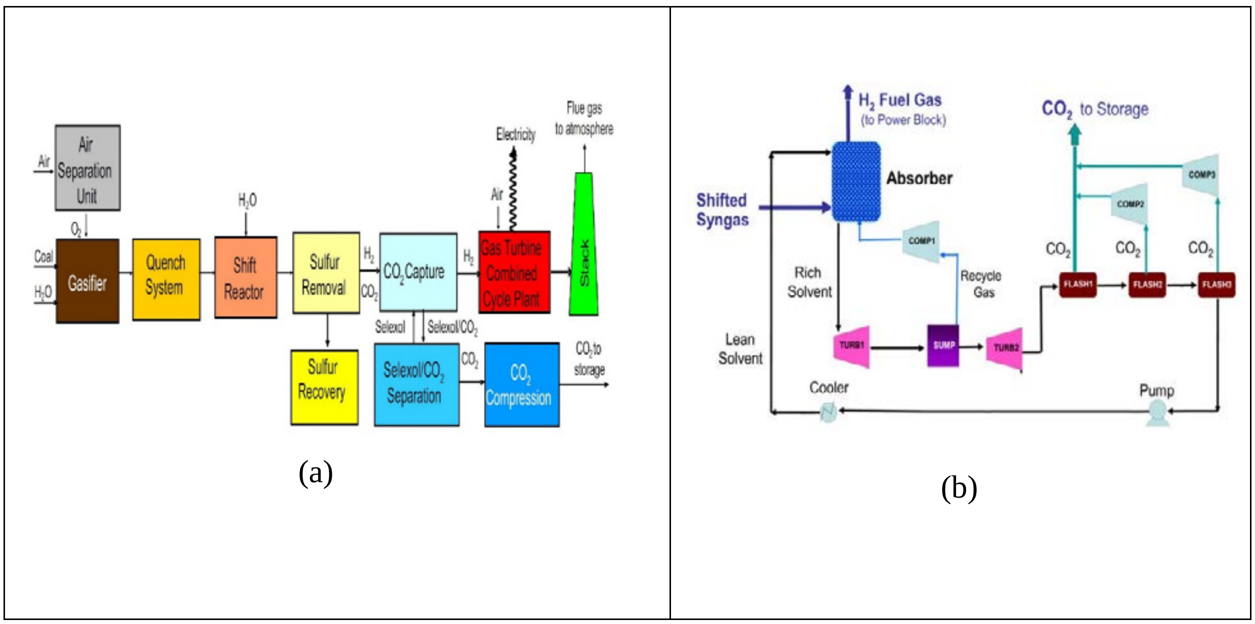

Fig. 3: A pre – combustion carbon dioxide capture of integrated gasification combined cycle (IGCC) coal power plant with the aid of water gas shift reactor and selexol carbon dioxide separating system [5].

The first major step conducted during the elimination of carbon from fuel is to change the fuel to a form that is quite easy to capture. A reaction between coal with steam and oxygen gas is the usual phenomenon for power plants fueled by coal and the reaction occurs at high temperature and pressure described as partial oxidation [13]. The end product of this reaction is a gaseous fuel made up of carbon monoxide (CO) and a mixture of hydrogen called synthesis gas or syngas. This gas can further go through a combustion process to produce electricity in a combined power plant. This method is often referred to as Integrated Gasification Combined Cycle (IGCC) power generation. In the second step of this process, the carbon monoxide obtained in first step is transformed into carbon dioxide via a reaction with steam. This leads to the formation of carbon dioxide and hydrogen.

Table 1: Current research on pre – combustion carbon capture

Year	Methods	Gas component	Brief description	References
2010	Chemical absorption	Synthesis gas	Several carbon dioxide capture methods were investigated and compared by methyl di – ethanol amine solutions	[14]
2011	Pressure swing adsorption	Pure carbon dioxide	Hyper – cross linked polymers were synthesized for carbon dioxide adsorption and gave carbon dioxide of 13.4 mmol/g at 30 bar and 298K	[15]
2012	Pressure swing adsorption	Carbon dioxide and Hydrogen	Three materials including USO – 2 – Ni metal organic framework (MOF), mesoporous silica MCM – 41, and a mixed material of UiO – 67 MOF bound with MCM – 41 were used	[16]
2012	Chemical absorption	Synthesis gas	Solvent made up of K_2CO_3 were used for carbon dioxide separation from the synthesis gas	[14]
2013	Pressure swing adsorption	Carbon dioxide and Hydrogen	An extensive parametric study of a pressure swing adsorption process for carbon dioxide capture was investigated	[17]
2015	Adsorption	Carbon dioxide and methane	Selectivity of carbon dioxide and methylene increased to 22.1 at 35bar and 333K using a mesoporous amine – TiO_2 sorbent	[18]
2015	Membrane	Carbon dioxide and hydrogen	Mixed matrix membranes made up of two-dimensional MOF nanosheets were investigated for carbon capture.	[19]

2015	Physical absorption	Carbon dioxide, Hydrogen sulfide, carbonyl sulfide	A two stage per combustion carbon dioxide capture process was designed and investigated using three physical absorbents	[20]
2016	Membrane absorption	Carbon dioxide and Helium	The selected absorbent of butyl – 3 – methylimidazolium tricyanomethanide showed high carbon dioxide absorption capacity	[21]
2017	Hydrate – based gas separation	Carbon dioxide and hydrogen	The CO2-H2-TBAF semiclathrate hydrate formation process was proposed	[22]

A glycol solvent, known as Selexol, is used to trap the carbon dioxide through a chemical process. This results in purified hydrogen gas which goes through another combined cycle power plant to produce electricity as shown in Fig. 3(a). The easy and cheaper separation of carbon dioxide because of the high operating pressure and excellent carbon dioxide concentration using IGCC plants makes them the mostly preferred option by the research community even though they are very expensive compared to the traditional coal combustion plants. The operational approach for pre-combustion capture includes physical absorption into the solvent, then releasing the carbon dioxide after the sorbent pressure drops, as shown in Fig. 3(b), instead of using a chemical approach to trap the carbon dioxide like using amine systems in post combustion capture. The use of IGCC involves some limitations as there are some loss in energy during the carbon dioxide capture because of the shift reactor and other steps involves in this process.

It is also possible to use pre – combustion carbon dioxide capture in power plants that utilizes natural gas. Using natural gas as fuel involves conversion of the gaseous fuel to syngas through reactions with oxygen and steam via a method called reforming. Concentrated carbon dioxide and hydrogen is produced [14 – 26]. It must be noted that this method is very expensive compared to using natural gas as fuel but in post combustion capture approach.

2.1.1 Separation techniques for the capture of carbon dioxide in Pre - combustion

Physical absorption

There are two main stages with the physical absorption process. These are the absorption and stripping process. The absorption process involves treated gas being in contact with solvent stream and the CO_2 being captured by the solvent physically. The stripping involves carbon dioxide and saturated solvent is introduced to heat to regenerate new solvent and releasing the CO_2 at the apex of the stripping column. The extent of CO_2 absorption for physical solvent is built around Henry's law. Dissolution of CO_2 in the liquid solvent is due to van der waals or electrostatic forces between them. Physical absorption is optimal at high pressure and low temperature. Other conditions like high temperature but low pressure affects physical desorption. Physical absorption has good absorption characteristics compared to chemical absorbent at high partial pressures of CO_2 [14,15]. Its regeneration can be achieved via depressurization operation at lpw energy demand. This is the main reason for their dominance in pre-combustion carbon capture technology. They are useful in IGCC power plants for removing CO_2 from synthesis gas, natural gas treatment and acid gas recovery as well. It must be noted that the absorption capacity of physical absorbent is useful at low temperature. It therefore implies that cooling treated gas streams before the absorption process is very important [16]. The well known physical absorption process involves Selexol, Rectisol, Purisol and Fluor method.

Adsorption

Adsorption is slightly different from absorption because adsorption includes specific formation of physical and chemical bonds between CO_2 and the solid phase adsorbent surface until the latter becomes saturated. The adsorbed CO_2 is then desorbed via pressure swinging (pressure swing adsorption (PSA) or temperature swing adsorption (TSA)) in order to regenerate the adsorbent material. The adsorbent which is saturated is heated in Temperature swing adsorption to temperature range at which physical and chemical bond is broken leading to the release of adsorbed species but for pressure swing adsorption the pressure is reduced to generate the same effect. When the CO_2 concentration is insignificant, temperature swing adsorption is often used but when the CO_2 concentration is high PSA is preferred [17, 18]. Pressure swing adsorption is useful because of its short temporal need for regenerating the adsorbent. At ambient conditions, adsorption is best in terms of high loading capacity, less energy intensive and impurities in flue gas. Some well known physical adsorbent are zeolite, carbon molecular sieves, silica membrane and metal organic framework materials (MOF). Chemical adsorbents include calcium oxide as well amine sorbents.

Membrane Technology

Knudsen diffusion principle is the phenomenon that leads to membrane separation. CO_2 dissolves in the membrane and diffuse through at rate proportional to its partial pressure gradient. Application of non-facilitated membrane technology is predominant in CO_2 elimination from natural gas and where the CO_2 partial pressure is high. In the capture of carbon from flue gas because the CO_2 is les, there would be more energy imposed because compression work is need to support enough driving force to obtain the required carbon capture ratio. Enhancement of it's selectivity is dependent on how permeable the membrane is designed to be. It implies that even though it has many merits like low environmental effect and degradation, integrating it to power plant already in existence poses a challenge. Researchers today are investigating on many ways of averting this challenge. The facilitated transport membrane separation is one of the newly designed approach recommended by researchers around the world. It is made up of mobile or liquid phase carrier that support movement of CO_2 as bicarbonate. This will support the permeability as well as the selectivity of CO_2 across the membrane. The mixed matrix membrane is also new type of membrane technology [19 – 21]. They are made up of polymer membranes impregnated with inorganic fillers. Some of the inorganic fillers are; carbon nano tubes, zeolite, mesoporous silica and zeolitic imidazolate. These modified membranes reduces the processing cost, increase selectivity as well as permeability. The mechanical strength and thermal stability of these membranes are very good. Another new types of membrane separation technology is the gas membrane contactor. These types of membranes are not dependent on the Knudsen diffusion approach. The membranes for the gas membrane contactor only act as a point of contact between the flu gas and the CO_2 absorption solvent. They show the compactness of the membrane system, high selectivity of amine-based absorption process and high flexibility for gas and liquid flow velocities. Their main demerits is that there are limitations in terms of mass transport because of resistance on the membrane framework.

Cryogenic Separation

This approach involves several cooling and compression operations at sub ambient temperature and high pressure for separating the gas components in the carrier stream. This technique is suitable for producing liquid carbon dioxide [21]. It is ideal for carbon dioxide capture in high concentrations. This technology can also be used in place of amine-based scrubbing method because it utilizes water in lesser quantity, uses cheap chemical agents, corrosion resistant and less effect on the environment in terms of pollution. This concept also supports ambient pressure operation as well as liquid CO_2. They therefore support CO_2 transmission economically. Cryogenic separation has some limitations too [22]. It is energy intensive due to the operating temperature range being low hence high cost of operation. Formation of ice in cryogenic approach often causes the piping system being blocked and this reduces the drop-in pressure causing safety issues. It therefore becomes important that the amount of moisture is removed before the separation process. This process adds to the initial cost of using this technology.

2.2 Post- combustion approach

The post combustion carbon capture (PCC) absorbs the carbon dioxide produced by the flue miasma after fossil commodities or materials made of carbons undergo a combustion process. The greatest quantity of electricity used by the world in recent times is obtained from power plants that functions through a combustion process. The main process in coalfired power plants used today is the combustion of pulverized coal fused with air in a boiler or a furnace [27]. The process is an exothermic reaction and the steam released is used to run a turbine generator shown in Fig. 4.

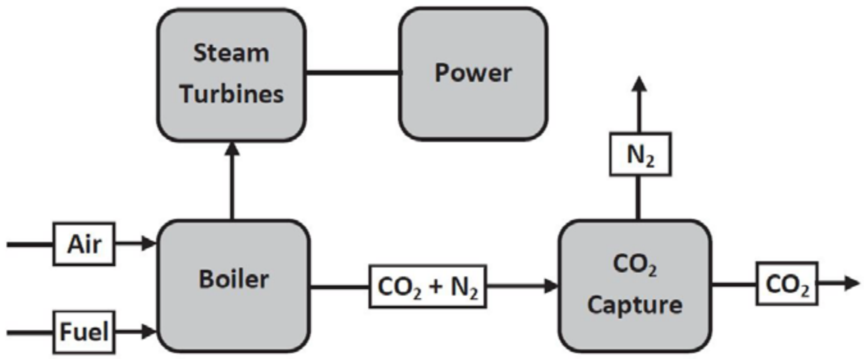

Fig. 4: A diagram showing post combustion carbon dioxide capture [27].

The high temperature gases that flows out of the boiler is made up of nitrogen from air and water vapor in smaller concentrations. There is also carbon dioxide produced from the hydrogen and carbon from the fuel used. Sulfide dioxide (SO_2), nitrogen oxide (NO) and fly ash (particulate matter) are also formed due to the burning of impurities in coal. These toxic gases and others like mercury must be eliminated as they are considered as pollutants according to emission standards [28]. In some situations, elimination of pollutants like SO_2 helps in the provision of pure gas stream for the capture of carbon dioxide [28]. Chemical reaction is described by scientists as the best way for the capture of carbon dioxide from flu gases of a pulverized coal plant but a solvent called monoethanolamine (MEA) is also required to facilitate the chemical reaction process. MEA is a member of the amine compound. The flue gas is first scrubbed in a vessel called an absorber. The absorber helps in the capturing around 85% to 90% of the carbon dioxide produced. The carbon dioxide in a form of a solvent is injected into another vessel named as the regenerator or the stripper. In the second vessel, the release of the carbon dioxide involves the usage of steam. The carbon dioxide produced after this process is highly concentrated [29]. The gas is then compressed and transported to a site where they can be stored. The solvent used in the process is the forced back and recycled to the absorber. A detailed post combustion capture of carbon dioxide is shown in Fig. 5 [30].

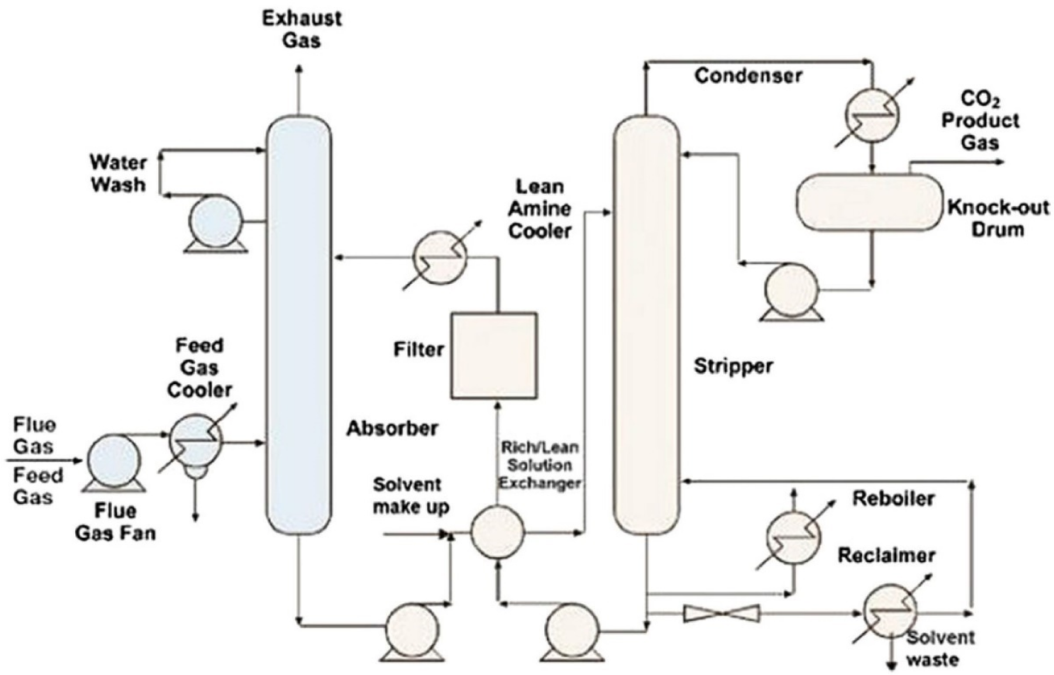

Fig. 5: Carbon dioxide capture from flue gas and sorbent flows of an amine type post combustion and the generator as well [27]

This technological approach is suitable capturing carbon dioxide at pulverized coal power plant as well as at a natural gas fired boiler or combined cycle (NGCC) power plant shown in Fig. 6. The coal plants often have the flue gas carbon dioxide concentration being denser compared to the NGCC, but it is still possible to obtain high removal efficiencies even with the amine based capture systems [31]. The natural gas has no impurities hence the flue gas stream is very clean. This implies that there will be no need for any cleanup in order to capture the carbon dioxide effectively [32, 33]. Table 2 captures the recent studies for post combustion in carbon dioxide capture.

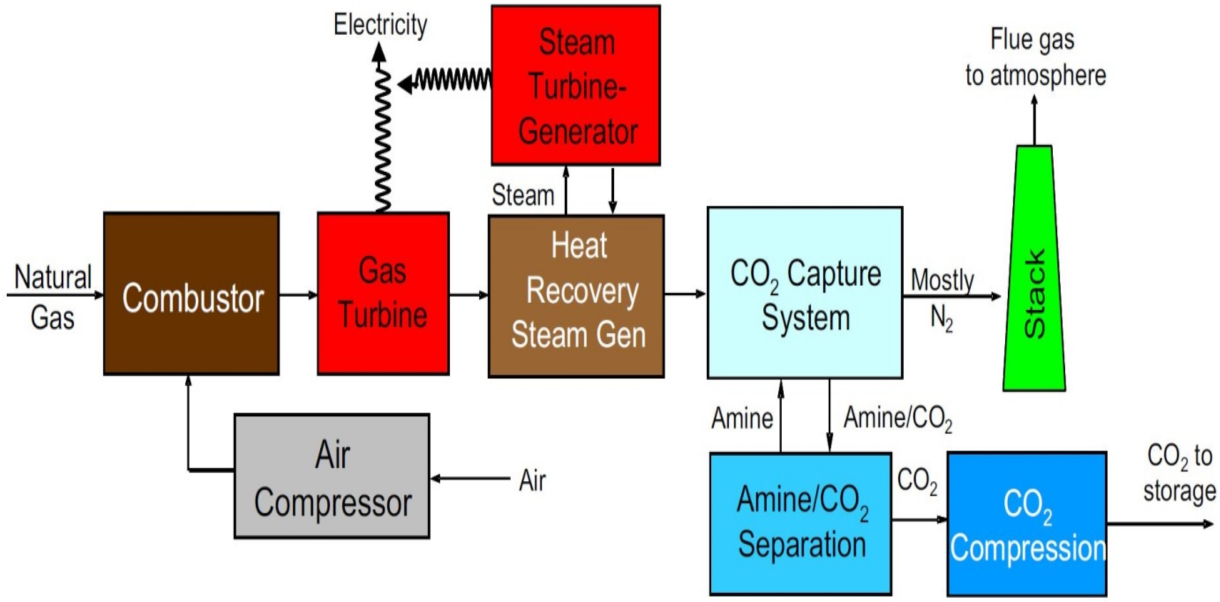

Fig. 6: A diagram showing an amine based post – combustion carbon dioxide capture system for NGCC power plant [27]

Table 2: Post combustion carbon capture

Year	Methods	Gas component	Brief description	References
2010	Pressure swing adsorption	Presence of flue gas	Nearly 98 percent of pure carbon dioxide was obtained after a synthetic process using pressure swing adsorption.	[34]
2010	Ionic liquid	-	A promising solvent for the absorption of carbon dioxide according to the investigation was ionic solvent	[35]
2011	Biotechnology	-	The process of post combustion carbon dioxide capture can be made faster through the usage of carbonic anhydrase according to this research work.	[36]
2012	Adsorption	Carbon dioxide and Helium	The work concluded that mixed – amine polyethyleneimine (PEI) as well as 3 – (aminopropyl)triethoxysilane are very good sorbent of carbon dioxide.	[37]
2013	Cryogenic separation of the membrane	Carbon dioxide and Oxygen	With a cost of 35 dollars per ton, the new membrane – cryogenic was described by researchers concluded as cost effective	[38]
2014	Adsorption of the membrane	Carbon dioxide and nitrogen gas	A numerical investigation was performed to determine the effect of membrane and contractor properties on carbon dioxide capture using methyl	[39]

			diethanolamine and 2-1- piperazinyl- ethylamine solvents.	
2016	Adsorption	Carbon dioxide and Nitrogen gas	An investigation was conducted to determine the effect of carbonization reaction mechanisms for carbon dioxide and potassium carbonate.	[40]
2016	Adsorption	Carbon dioxide and Nitrogen gas	An investigation was performed to explore the possibility of capturing carbon dioxide using PEI – impregnated, millimeter sized mesoporous carbon spheres.	[41]
2016	Membrane absorption	Carbon dioxide and Nitrogen gas	An experimental research was performed for carbon dioxide capture and their conclusion gave a better result.	[43]
2017	Chemical absorption	Carbon dioxide and Nitrogen gas	The carbon dioxide were captured using formulated, reactive, blended amine solution.	[44]

2.3 Oxy – combustion approach

As an alternative to post–combustion process, the oxy–combustion method has recently been developed as CO_2 capturing technology. This process uses pure oxygen in the combustion process and this reduces the quantities of nitrogen in the flue gas stream. The fly ash is also removed from the flue gas stream resulting in the flue gas which only made up of carbon dioxide and water vapor and some impurities such as sulfur dioxide and nitrogen oxide. Compression and cooling of the flue gas is one of the mediums used in the removal of the water vapor. This process leaves behind pure carbon dioxide which is storage directly as shown in Fig. 7. One advantage of oxy – combustion over post combustion is the avoidance of an expensive carbon dioxide capture system for post combustion. In place of a carbon dioxide capture systems for post combustion, the oxy combustion uses air separation unit (ASU) to produce clean oxygen with around 95% to 99% purity for oxyfuel systems compared to IGCC plant of the same size. The ASU affects the cost significantly. Extra gas processing is often needed to limit the air pollutant concentration in order to meet the correct environmental guideline. This will further reduce a build of unwanted materials in the flue gas recycle.

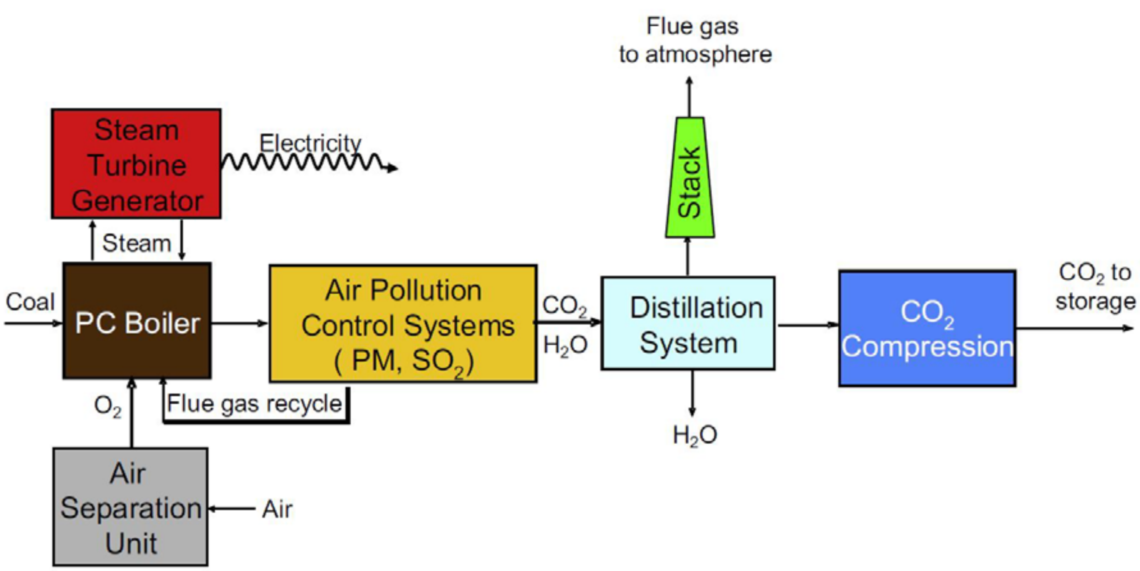

Fig. 7: Oxy – combustion technology utilized in a coal fired power plant [34].

The temperature of combustion using pure oxygen is greater than that of air hence oxy combustion involves huge portion of the stream for the flue gas being used back in the boiler to maintain optimal operating temperature. Recent oxy fueled boilers come in designs to reduce recycle using slagging combustors or non – stoichiometric burners. Sealing of the system is another important stage in the system design in order to maintain the required oxygen and nitrogen found in the flue gas. The sealing prevents air leakages into the flue gas. This is considered as one of the most difficult maintenance issues because the leakages at the flanges and joints are difficult to prevent especially along the flue gas duct. There has been several research work conducted on 30MW thermal plant that uses the oxy combustion technology. Oxyfuel systems requires gas treatments to eliminate pollutants from the system and this reduces the efficiency of the system to 90%. It is possible to apply the concept of oxy combustion in a simple cycle or combined cycle power plants using natural gas or distillate oil. Table 3 also shows some current research conducted using the oxy combustion technology.

Table 3: Recent investigation using oxy combustion technology [34]

Year	Methods	Gas component	Brief description	References
2011	-	Flue gas	Carbon dioxide capture using integrated oxy combustion and $Mg(OH)_2$ was investigated.	[44]
2011	-	Flue gas	The effect of sulfur on the capture of carbon dioxide via a process using oxy combustion was researched.	[45]
2015	Oxygen transport membrane	Flue gas	An investigation into the characteristic performance of advanced steam cycle power fitted with a carbon dioxide capture using oxy fuel combustion was thoroughly investigated.	[46]
2016	Oxygen transport membrane	Flue gas	Carbon dioxide selectivity as well as well as permeability of oxygen was investigated using oxygen transport membrane reactor. The membrane reactor showed high carbon dioxide absorption of 87.1%.	[47]

Fig. 8 shows the carbon capture and storage technology as well as sources from different commodities like cement, steel production and bioethanol plants. The bioethanol plants produce food grade carbon dioxide from fermenters. This investigation explores the main technological advancement made in recent times with respect to carbon capture [48]. Table 4 shows some state of the art.

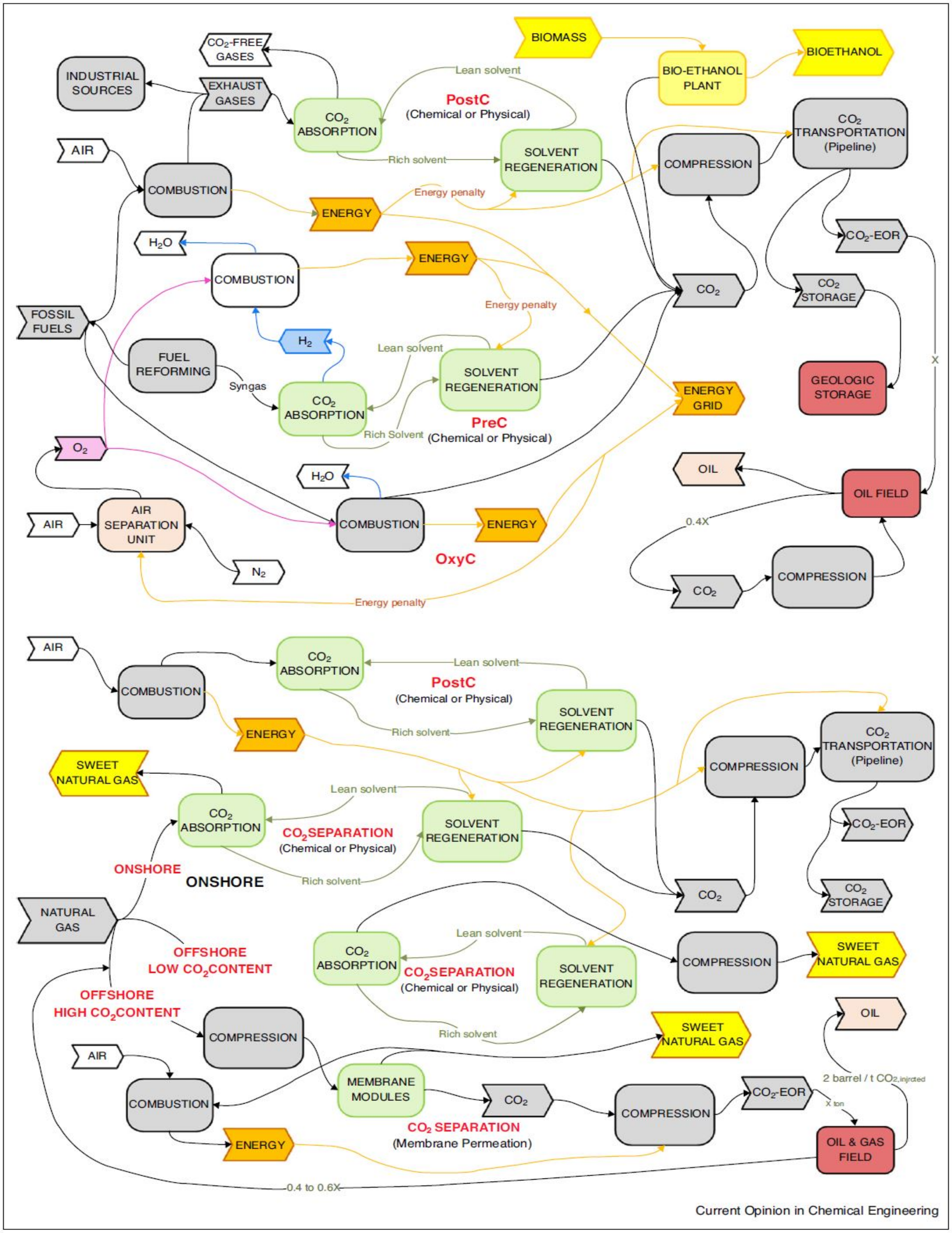

Fig. 8: Recent state of the art carbon dioxide capture routes [34]

Table 4: Technologies for carbon dioxide capture (State of the art technology at commercialization)

Technological advancement	Merit	Obstacle and literature gap	Ref
Absorption via chemical means	It is considered a matured kind of technology for natural gas and post combustion. It is also suitable for power plants fired by carbon. The efficiency for capturing the carbon dioxide is very high and losses with respect to hydrocarbons is low.	The capture ratio and heat ratio are very high. For power plants operated using coal, there is high capture energy penalty of approximately 20 – 30 percent. Challenges relating to corrosion, emissions and solvent degradation. Solvent challenge relating to thermochemical stability, reduction in capture ratio, heat ratio and stripping temperatures to facilitate the usage of waste heat.	[48] – [55]
Physical absorption	Has high capture efficiency. Very suitable for power plants fired by coal. The capture efficiency is very high but the heat ratio is low for regeneration. This is also considered a matured technology for processing of natural gas and post combustion.	The selectivity is low with high hydrocarbon losses.	[55], [56]
Membrane penetration	Suitable for natural gas processing on large scale. Does not require regeneration, no chemicals, low footprint, adequacy through carbon dioxide partial pressure.	Compression of natural gas is needed. There is high hydrocarbon losses and trade off permeability selectivity.	[57] – [59]

Pre combustion	Appropriate for power plants fired by coal. Cost effective, suitable for hydrogen production in commercial quantities. Has highly efficient, approximately 10 – 15% low capture energy penalty.	It is very complex, requires new materials for high carbon dioxide capture at high temperature, huge capital expenses, still undergoing developmental processes. The experience for large scale hydrogen fired power plant is still inadequate	[60], [61]
Cryogenic distillation	This is also a matured technology for natural gas with high carbon dioxide composition, high selectivity, little hydrocarbon losses. There is no need for compression as the carbon dioxide is obtained in liquid state hence transportation is easy and simple. Suitable for high carbon dioxide composition.	Avoiding the carbon dioxide freeze out is very necessary and also refrigeration energy penalties.	[55]

Table 5: Other technology for carbon capture but with insufficient large-scale experience

Technological advancement	Characteristics	Merits	Ref
Hybrids	High carbon dioxide elimination via cryogenic distillation or membrane permeation and polishing through chemical or physical absorption.	The cost is very low and the capture energy penalty is low as well	[62]
Enhancement of chemical or physical absorption	Flowsheets are complex and requires mixed solvents.	The equivalent work needed is 12 percent less compared to a stripper. There is high heat ratio reduction because of the usage of the mixed solvents instead of MEA in liquified state. The thermochemical stability is very high.	[63]
	The solvents have high efficiency	Reduced heat ratio	[64]
	Hybrid solvents		[65]
	Requires solvents that are anhydrous, outstanding task specific ionic liquids and carbon dioxide bonding organic liquids.	The vapor pressure is low removing fugitive stripping emissions in regeneration. Being anhydrous, the challenge in relation to high parasitic energy consumption regarding water is reduced.	[66], [67]

	Ionic liquid Solvents that undergoes phase change Addition of inert solvent for carbon dioxide solventing out Metal – organic solvents	Reduced heat ratio, reduced evaporation losses. Reduced heat ratio, loading of the carbon dioxide results in phase change. Requires using waste heat in solvent regeneration Low heat ratio	[68] [69] [53] [70]
Membrane penetration	New membrane materials	High flux but the exhaust gases have low pressure but high carbon dioxide permeable and selective membrane application.	[71]

	Metal oxide framework membranes Dense mixed conducting membranes Integrated membrane material and process development for gas separation Multi stage schemes The sweep agent used is steam. For lean carbon dioxide flue gas, driving force is low but this condition is different for compressed fed. Solvent supported membrane	Superior thermal and chemical stability Superior thermal and chemical stability Sustainable membrane permeability Highly efficient Efficient permeate elimination, avoiding carbon dioxide buildup, limiting the membrane area for exhaust gases even at low carbon dioxide content. Solvent with negligible volatility (ionic liquids and deep eutectic solvents) to increase selectivity.	[72] [73] [74] [75] [76] [77]
Gas liquid membrane contactors	Synthesis, characterization and performance of various membrane materials, contactors and their aspects	High efficient, high modularity, independence of gravity, no flooding effects	[78]

Adsorption	Novel sorbent materials example residues from industrial and agricultural activities, metal organic framework.	High surface area, high selectivity and high regeneration ability, reducing energy penalty.	[66]
Oxy combustion	Makes post combustion capture simplified and also very efficient.	High efficiency, reduced capture energy penalty	[79]
Chemical looping combustion	Uses metal oxide as oxygen carrier, which is reduced to oxidized fuel to carbon dioxide and water being regenerated in the second stage	Low capture energy penalty	[80]
Mineralization	Conversion to a solid material	Commercialization	[81]

2.4 Comparison of the various carbon capture capacity between 2006 - 2018

Carbon capture and storage is a large-scale separation of CO_2 from well-known sources followed by long term isolation from the atmosphere and its usage in futuristic terms. It is an end of pipe solution designed for a situation where high emissions of carbon dioxide due to high energy demand, industrial intensification and high dependency on fossil commodities becomes inevitable. This method is useful for carbon sequestration from large scale carbon dioxide point sources. The well know areas where carbon capture and storage can be utilized are power generation and heavy chemical manufacturing sectors. From Fig. 9, the energy related anthropogenic carbon emissions exceeded 32.27 billion tonnes in 2012. Researchers anticipates that by the year 2020, this figure is likely to increase appreciably to 35.63 billion and 43.22 billion by 2040. This increase according to researchers will emanate largely from developing countries. Only 33.4 million tonnes of carbon dioxide can be captured annually in spite of all the carbon capture and storage facilities across the world. This is 0.09% of the total projected carbon emissions. To combat climate change, expansion of carbon capture and storage technology will be a necessity.

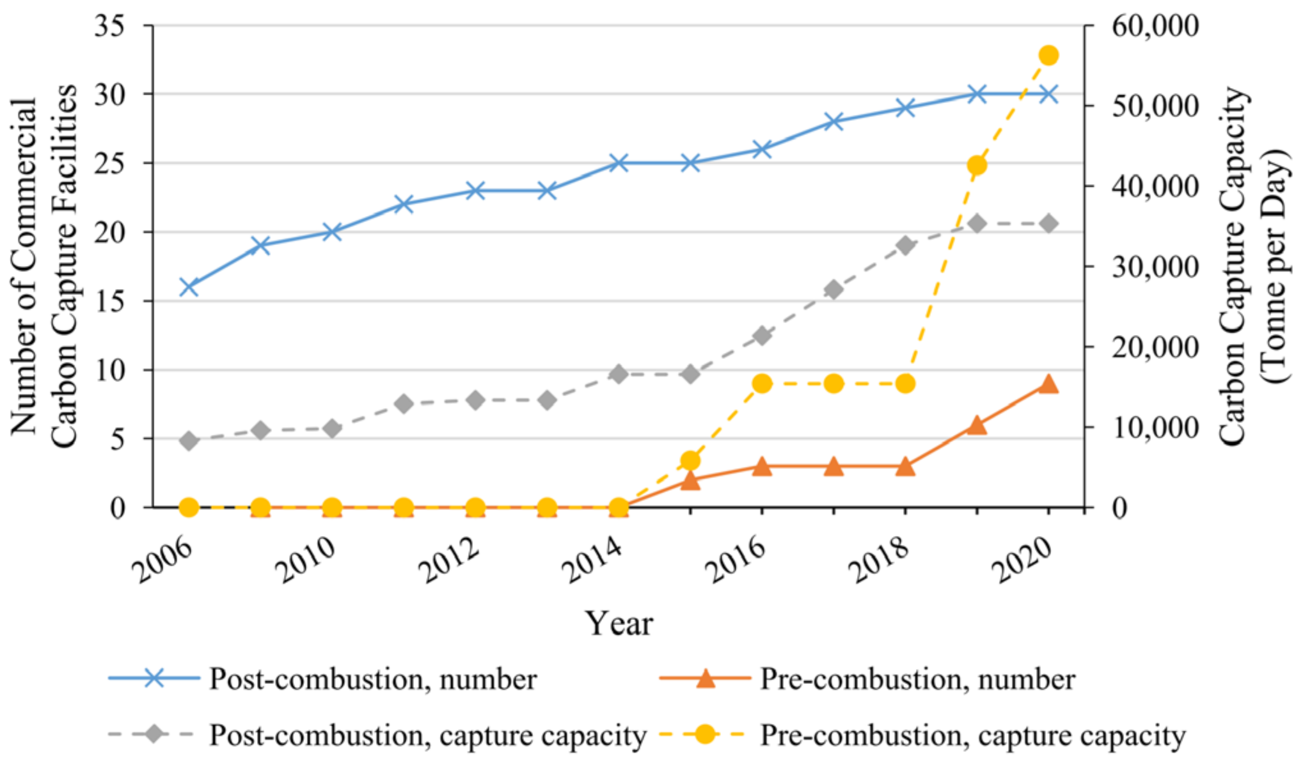

Fig. 9: Commercialized carbon capture technology across the world

From Fig. 9, it is observed that between the year 2006 to 2018, the number of commercial carbon capture facility for post combustion has surged up from from 16 to 30. This indicates a high increase compared to pre combustion. It therefore explains the increase in carbon capture capacity from 26000 Tonnes per day in 2006 to 50,000 tonnes per day in 2018. Pre – combustion was nearly zero between 2006 to 2014 but after 2014, the capacity has increased to nearly 7000 tonnes per day in 2018.

Table 6 captures comparison between the three main CCS technologies, i.e. post combustion, pre-combustion and oxyfuel combustion. Fig. 9 explains projected values for commercialized carbon capture facilities and capture capacity across the world. The main industrial and power plants that have already adopted CCS technologies are shown in Table 7 and Table 8. From Table 6, it is observed that oxyfuel combustion capture system presently has no operational full-scale carbon capture storage plant. The most established carbon capture and storage technology is the post combustion technology. Solvent development and process intensification for post combustion carbon capture using chemical absorption are well developed. Researchers are also investigating on solid sorbent technologies in order to improve their performance. High regeneration enthalpy, thermal and oxidative degradation of amine based solvents and low carbon dioxide partial pressure constraint are some challenges relating to this technology. Pre combustion technology is described as the best alternative to mitigate this challenge. A clear comparison for all the three types of carbon capture and storage technology is shown in Table 6.

Table 6: Comparison of the various carbon capture technology

Technical Issue	Post Combustion Capture	Pre-Combustion Capture	Oxyfuel Combustion Capture
Maturity of Technology	Matured type of technology utilized in many well known applications at commercialized level	Dominant in process industry especially water gas shift reaction fixed with acid gas removal (AGR) process. Establishment of full scale carbon capture and storage plants under progress.	There are presently no full scale oxyfuel carbon combustion and storage plant operating. This technology is also limited to pilot scale operations to date.
Merits	Very compatible for reconstruction of power plants already in existence and this helps in consistent usage of common power plant generating technology like pulverized coal. There is also extensive research to enhance the efficiency of energy obtained from post combustion carbon capture equipment	The CO_2 separation process is less energy intensive because of low gas volume, high pressure and high carbon dioxide concentration. Acid gas removal process presently are used in several technologies commercially. The water consumption for this technology is also low compared to post combustion capture. There is also generation of hydrogen and synthesis gas as alternative fuel.	Emission of pollutant is reduced. There is also no need for chemical operations on site. The technology is robust implying that it is compatible with other type of fuels. It is also easy and simple to retrofit compared to post combustion capture system. There is also high carbon capture efficiency (on cost per tonne CO_2 sequestered basis due to high carbon dioxide concentration) Reduced equipment size requirement. High maturity of air

			separation technology. Highly compatible with conventional high efficient steam cycle without significant modifications. Highly established auxiliary equipment i.e rotating equipment and heat exchanger.
Demerit	Separation constraint due to low CO_2 partial pressure in flue gas. Commercially available amine scrubbing technology is often of small scale and demands substandard upscaling. Significant energy penalty of amine scrubbing process (i.e loss of 30% overall power output). Requirement of energy intensive CO_2 compression. Most sorbent technologies are less robust with high performance requirement. High water consumption	High energy loss because of sorbent regeneration (even though it is low compared to post combustion capture. Limited commercial availability of integrated gasification combined cycle (IGCC) technology. High auxiliary system requirement by IGCC technology. Syngas temperature swing associated with heat transfer problem. Reduced efficiency associated with hydrogen fueled gas turbine application.	Infeasible development of sub scale oxyfuel combustion capture technology. Net power output reduction due to energy intensive air separation unit (ASU) and carbon dioxide compression. Technical uncertainties associated with operation of full scale plant remain unresolved. Requirement of air tight installation to avoid air leakage (or carbon dioxide leakage due to over pressurized operation). Possible corrosion problem.

Economic aspect	Ver expensive technology in terms of capital and operational expenditures because large equipment size is required (i.e large flue gas volume) Capital cost Gas Fired: USD 870 per kW Coal Fired: USD 1980 per kW Electricity Cost Gas Fired: USD 0.097 per kW Coal Fired: USD 0.075 per kW	IGCC capital cost is far higher than that of conventional coal power plant. High capital and operational expenditure for sorbent technology Gas Fired: USD 1180 per kW Coal Fired: USD 1820 per kW Electricity Cost Gas Fired: USD 0.097 per kW Coal Fired: USD 0.069	High capital cost for air separation technology Gas Fired: USD 1530 per kW Coal Fired: USD 2210 per Kw Electricity Cost Gas Fired: USD 0.100 per kW Coal Fired: USD 0.078 per kW

Table 7: Commercialized post combustion technology applications across the world.

Application	Year of Operation	Installed capacity	Technology used in the capture of CO_2	Produced carbon dioxide fate	Reference
Prosint Produtos Sintéticos, methanol production plant (Rio de Janeiro, Brazil)	1967 - date	90	Fluor’s Econamine FG Plus Process	Food-grade CO2 production	[32]
Kerr-McGee’s soda ash plant (Trona, California, USA)	1978 - date	800	Kerr-McGee/ABB Lummus Crest Process	Production of soda ash and liquid CO2	[33]
Lubbuck natural gas processing facility (Texas, USA)	1982 - 1984	1200	Fluor’s Econamine FG Plus Process	Enhanced oil recovery (EOR) application	[82]
Indo Gulf Corporation Ltd, fertiliser plant (Jagdishpur, India)	1988 - date	150	Kerr-McGee/ABB Lummus Crest Process	Urea production	[83]
300 MW coal-fired cogeneration plant (Poteau, Oklahoma, USA)	1991 - date	200	Fluor’s Econamine FG Plus Process	Food-grade CO2 production	[32]
Soda Ash Botswana soda ash facility	1991 - date	300		Soda ash production	[84]

Bellingham natural gas combined cycle power plant (Massachusetts, USA)	1991–2005	330		Production of food-grade CO2 for beverage production	[85]
Sumitomo Chemicals (Chiba, Japan)	1994 - date	165		Food-grade CO2 production	[86]
Liquid Air Australia (Two plants)	1995 - date	60		Food-grade CO2 production	[32]
Statoil's Sleipner natural gas processing facility (Norway, North Sea)	1996 - date	2466	Amine scrubbing system	Oceanic storage at deep saline (Utsira) formation, 800–1000 meters below the sea bed	[87]
Petronas Fertiliser, steam reformer of fertiliser plant (Kedah, Malaysia)	1999 - date	160	MHI KM-CDR Process (using KS1 solvent)	Urea Production	[88]
Warrior Run 180 MWe coal-fired power plant (Cumberland, Maryland, USA)	2000 - date	330	Fluor's Econamine FG Plus Process	Food processing, refrigeration and fire extinguisher production	[89]
Shady Point 320MWe coal-fired power plant (Oklahoma, USA)	2001 - date	800	Kerr-McGee/ABB Lummus Crest Process	Food and beverage processing, freezing and chilling purposes	[32]

Chemical company, natural gas and oil-fired boiler (Kyushu, Japan)	2005 - date	330	MHI KM-CDR Process (using KS1 solvent)	General use product	[33]
IFFCO/AONLA fertiliser plant (Aonla, India)	2006 - date	450		Production of urea, NPK, DAP, and NP	[85]
IFFCO/PHULPUR fertiliser plant (Phulpur, India)	2009 - date	450			[86]
Nagarjuna Fertilisers & Chemicals Ltd (Kakinada, India)	2009 - date	450		Urea/ammonia production	[32]
Gulf Petrochemical Industries Company (GPIC) (Sitra, Bahrain)	2009 - date	450		Urea and methanol production	[33]
Ruwais Fertiliser Industries, natural gas reformer (Abu Dhabi, United Arab Emirate)	2010 - date	400		Urea production	[81]
Vietsovpetro White Tiger Project, Pyu-My 4000MW	2011 - date	240		Enhanced oil recovery (EOR)/ enhanced gas	[87]

gas turbine combined cycle power plant (Pyu-My, Vietnam)				recovery (EGR) application	
Engro Chemical Pakistan Limited (ECPL), urea fertiliser plant (Pakistan)	2012 - date	340		Urea production	[88]
National Fertiliser Ltd, Vijaipur plant (Madhya Pradesh, India)	2014 - date	450		Urea production	[89]
Qatar Fuel Additives Co. Ltd (QAFAC), methanol plant (Mesaieed, Qatar)	2016 - date	500		Methanol synthesis (yield enhancement)	[90]
Petra Nova Carbon Capture and Storage (CCS) Project, W. A. Parish coal-fired power plant (Texas, USA)	2014 - date	4776		EOR at mature West Ranch Oil Field (Texas, USA)	[91]

Saskpower's Boundary Dam Power Station (Saskatchewan, Canada)	2017 - date	2740	Cansolv Technology Inc. CO2 Capture Process	EOR at Weyburn Oil Field	[32]
ROAD CCS Project, 1GW coal-fired power plant (Rotterdam, The Netherlands)	2017 - date	3014	N/A	Storage at depleted gas reservoir	[85]
Peterhead Project, 385 MW combined gas cycle turbine power plant (Scotland, United Kingdom)	Completed by 2019	2740	Cansolv Technology Inc. CO2 Capture Process	Offshore storage at Goldeneye gas reservoir	[91]
Bow City Power CCS Project, 1000 MW supercritical coal-fired power plant (Alberta, USA)	2011 - date	2740		EOR	[32]
Shengli Oil Field EOR Project, Sinopec Qilu No.2 fertiliser plant (Shandong, China)	2017 - date	2740	N/A	EOR in Shandong Province	[82]

Taweelah Project, natural gas-based TAPCO and EMAL power plants (Abu Dhabi, United Arab Emirates)	Completed by 2018	5479	N/A	EOR	[32]

Table 8: Commercialized pre combustion technology applications across the world.

Application	Year of Operation	Installed capacity	Technology used in the capture of CO_2	Produced carbon dioxide fate	Reference
Hydrogen Energy California Project, Hydrogen/petroleum coke-fuelled integrated gasification combined cycle (IGCC) power plant (California, USA)	Built in 2015. Operation starts in 2020	8219	Rectisol AGR system	Onshore enhanced oil recovery (EOR) at Occidental's Elk Hills Oil Field	[32]
Texas Clean Energy Project, Coal-fired power plant (Texas, USA)	By 2019	5479 - 8219	Rectisol AGR system	EOR at Bermian Basin	[32]
Kemper County IGCC, Pre-combustion IGCC plant (Mississippi, USA)	2016 - date	9589	TRIG^{TM} Technology	Onshore EOR	[85]
Killingholme Project, IGCC power plant (North Lincolnshire, United Kingdom)	By 2019	6849	Selexol process	Storage at deep saline formation	[81]

Don Valley Power Project, Coal-fuelled IGCC power plant (South Yolkshire, United Kingdom)	Built in 2013. Operation in 2019	13,425	Selexol process	Offshore storage at deep saline formation	[80]
Dongguan Project, Coal-fired 800 MW IGCC power plant (Dongguan, China)	Operational from 2013	2740	TRIG^{TM} Technology	EOR in Shandong Province	[32]
Huaneng GreenGen Project, Coal-fired 400 MW IGCC power plant (Bohai Rim, China)	By 2020	5479	N/A	EOR	[32]
Lianyungang Project, Coal-fired 1200 MW IGCC power plant (Jiangsu, China)	2015 - date	2740	N/A	Oceanic storage at Binhai and EOR at North Jiangsu Oil Field	[32]

3. Transportation and storage of captured CO_2

The captured carbon dioxide always needs to be transported from the capturing site to the storage site. The key consideration that should be taken during the transportation of carbon dioxide are the compression of the gas to a supercritical state, pipeline corrosion and the effect of fluid composition on the power that will be consumed [51]. This can be achieved by recompressing the pipeline at distance beyond 150 km. Transporting the carbon dioxide using pipelines in bulk reduces the overall cost of the carbon capture and storage system. This is considered a matured technology in the carbon capture and storage system. For over 40 years, this technology has been adopted in the transportation of 50 Mtpa carbon dioxide via 3600 miles [104]. Sharing the transportation network is one method of reducing cost. An in depth knowledge on the thermodynamic and transport characteristics of carbon dioxide mixtures is very necessary when designing a carbon capture system. Majority of the overall cost for the transportation and storage of the carbon dioxide in a carbon capture and storage system occurs at the compression stage of the carbon dioxide stream. An attempt to capture carbon dioxide at higher pressure reduces the compression power at downstream.

In the last few decades, several geological sites have been used for storing CO_2 such as saline aquifers, depleted basins and enhanced oil recovery [105]. There are some requirements for any storage sites to be suitable for storing CO_2. The formation of the site must be porous and permeable for easy injection of huge volumes of carbon dioxide. Also, it must have rock caps for the imprisonment of the carbon dioxide and prevention of any potential leaking. Storing carbon dioxide in an abandoned oil field is also appropriate because most of these sites become impermeable after holding oil and gas for several years. These reservoirs have some disadvantage as well as they are often penetrated by other wells damaging the seal. Retaining the carbon dioxide carbon dioxide is achieved through a trapping mechanism: a) stratigraphic and structural (primary trapping occurs beneath seals of low seals of low permeability rocks, dominant at early stage); b) residual (Using water capillary pressure, trapping is achieved via rock pores c) Solubility (residual gas trapping) and d) mineralization (changing the pore – space topology and connectivity). There is precipitation of carbonates at the last stage of the storing process and this is likely to block the pathway for the fluid and there is also finally a loss of the storage pore volume [105].

Other researchers investigated the direct relationship between injection and induced seismicity for a long term and concluded that this storage process could lead to earth quakes but the leakage of carbon dioxide is not a major challenge in terms of scaling up carbon capture and storage systems. The cost for the injection is approximately 0.5 – 8 $\$/tCO_2$. A combination of enhanced oil recovery with a storage system will reduce the overall cost.

4. Application of the various CCS technologies

For commercial and industrial power plants, post-combustion carbon dioxide capture is considered the matured type of technology compared to the others. . Using solvent for the carbon dioxide capture is very important in post-combustion in the capture of carbon dioxide. Today, researchers are also exploring the various type of solvent, design and an integrated solvent design for the capture of carbon dioxide. Other investigations into the selection systematically and design of solvent for post-combustion carbon dioxide capture using several predictive methods have all been explored [106,107]. Several computational and statistical strategies have all been used during the investigation. For instance, the fluid theory family approach and quantitative structure property relationship have all be utilized during the conduction of an investigation [108,109]. Using universal quasi – chemical functional group activity coefficient approach has been designed for the capture of carbon dioxide [110]. Other researchers attempted the possibility of adding the solvent selection process with the carbon dioxide capture process [111-118].

For renovation of existing power plants, post combustion carbon dioxide capture is considered the best of options. This method has thoroughly been investigated as a medium of enhancing the performance of any equipment. As explained earlier, several numerical studies and modelling research work has been conducted using the approach [119]. Due to the gas volume being low, pressure being high and the amount of carbon dioxide also being high, less energy is often required for pre combustion carbon dioxide. Less amount of water consumption is observed for pre-combustion compared to post-combustion. An alternative fuel generated for pre-combustion is hydrogen/syngas [120]. The oxyfuel – combustion is considered more environmentally friendly compared to the other two methods. There is no need for any operations being done chemically for this types of carbon dioxide capture technology and also suitable for several types of coal fuels [121-125]. It is simple to renovate it compared to the other types like the post-combustion capture system. This approach has high efficiency in terms of carbon capture. Some advantages of this type of carbon dioxide capture technology is the fact that the equipment size is reduced, the air separation technology is high, it is well suited for conventional, efficient steam cycle with less modifications and the removal of NOx control as well as the carbon dioxide separation stage makes it very advantageous [126-132].

4.1 Capturing of carbon from exhaust gases

There is always a capturing energy penalty of 15 to 30 percent for power plants operated using carbon and this contributes to almost 60 - 85 percent of the carbon capture and storage expenditure [82-86]. To develop a carbon fired plant with an efficiency of 33 percent involves decreasing the power output by 1/3 and this increase the capital expenditure to approximately 77% [87]. Power plants fired by carbon have varying carbon dioxide emissions because of the variation in the fuel used but power plants fired by coal produces 1116 gCO_2/KWh at 30 percent and 669 gCO_2/kWh at 50% efficiency [88]. Even though coal is considered carbon dioxide intensive option, expansion in terms of capacity shows that initiatives for carbon mitigation are low compared to the economic incentives for a relatively cheap fuel. In terms of capital expenditure, natural gas fired power plant is better than power plants fired by coal since half of the capital expenditure for coal fired power plant is required for natural gas powered plant [89]. The overall performance uncertainties are estimated probabilistically [91]. Uncertainties with regards to the capital expenditure are very high at an approximated value of 40% although variability has little influence on the levelized cost of energy (LCOE) [92]. This shows that the operational costs (OPEX) determines the overall cost of carbon capture and storage. Other investigators reported that post combustion capture of carbon dioxide capture using chemical absorption is the most effective and cheapest means of carbon capture and storage technique [94]. The main obstacle is heat demand which increases the operational cost and this also reduces the power capacity. Power plants fired by carbon via hybridization using solar aided post combustion improves the overall efficiency of the plants. There is limitation in terms of the driving force for state of the art membrane permeation compared to chemical absorption in the capture of carbon dioxide from exhaust gases [95]. The reliance of fossil commodities when using coal fired plants can be replaced using renewable energy and this will reduce the fossil commodity that will go into combustion. The energy obtained from renewable energy being intermittent implies that the unit for capturing the carbon must be flexible in order to enhance the economics of the carbon capture. Flexibility is obtained by storing the solvent, removing energy generation from the capture of carbon dioxide to meet energy prices at peak times [96]. The flexibility of capturing unit helps in reducing the capital expenditure to 28 percent [95]. Capture energy penalty is reduced due to variable capture aligned to energy demand and dispatch and this often leads to increasing net efficiency and capacity [97]. A practical example is the absorber sized for a time average condition cost approximately 4 percent less than when it is sized for peak energy generation [97].

4.2 Carbon dioxide capture from Natural Gas

Similar to post combustion, natural gas is also dominated by precisely physical absorption [98]. Natural gas processing for Floating Production Storage and Offloading (FPSO) is slightly different from other natural gas processing. For natural gas processing of FPSOs, small area creates a technology niche for membrane permeation because it has low foot print and modularity. For instance the first PFSO started operation in 2010 for the Brazil pre sal oil and gas field [99] and they used membrane separation for separating carbon dioxide. Seven PFSO were being operated actively in 2016 [100] and six out of the seven were functioning via membrane permeation with each processing approximately 4 – 7 MMscmd of natural gas with almost 20 % of carbon dioxide [101]. One of the key factors for the selection of natural gas processing technology is the partial pressure of carbon dioxide in raw natural gas and plant location. Chemical absorption is suitable for low carbon dioxide feed that is less than 20 % because higher carbon dioxide content increases solvent recirculation rate and heat duty. Membrane permeation is best suited for medium to higher carbon dioxide partial pressure compare to chemical absorption. Other high carbon dioxide content project could be found in pre -salt field in Brazils' offshore pre oil field (Libra: 48 percent, Jupiter 78%) and La Barge gas field in Wyoming in the United States but these projects function using cryogenic distillation. The main merit of these projects is the fact that the carbon dioxide produced comes in liquid form which helps in their easy transportation via a pipeline but this advantage come with some challenge as well. When temperatures are low and the liquid is being operated at higher pressures, the carbon dioxide may freeze out and this will required the need for other complex technology like the Ryan Holmes process [101]. Today, the scientific community has explored several innovative means of gas and liquid transportation like the Ormen Lang project where natural gas and monoethylene glycol as anti hydrate are transported via two subsea 120km pipelines [102]. Natural gas in their raw state today can be channeled to an onshore facility for the separation of the carbon dioxide and fractionation of natural gas liquids and the carbon dioxide piped back to an offshore facility [103]. Hybrid processes often uses cryogenic distillation for huge separation, reducing carbon dioxide composition so that chemical or physical absorption can be implemented [104]. Another research conducted was hybrid natural gas processing using membrane permeation for higher removal and chemical absorption [105].

5. Future research/ development cost and challenges of CCS

The high cost of carbon capture technology poses a challenge towards the advancement of the technology. Fig. 10 below shows the cost of electricity produced from the different types of technologies under investigation. The left region of the figure explains current technologies with zero carbon options. The mid region of Fig. 10 depicts emerging technologies and the right region shows the cost of innovative systems. The dotted line shows near term electricity prices. The prices for all near zero carbon technologies are very expensive compared to current electricity cost [133].

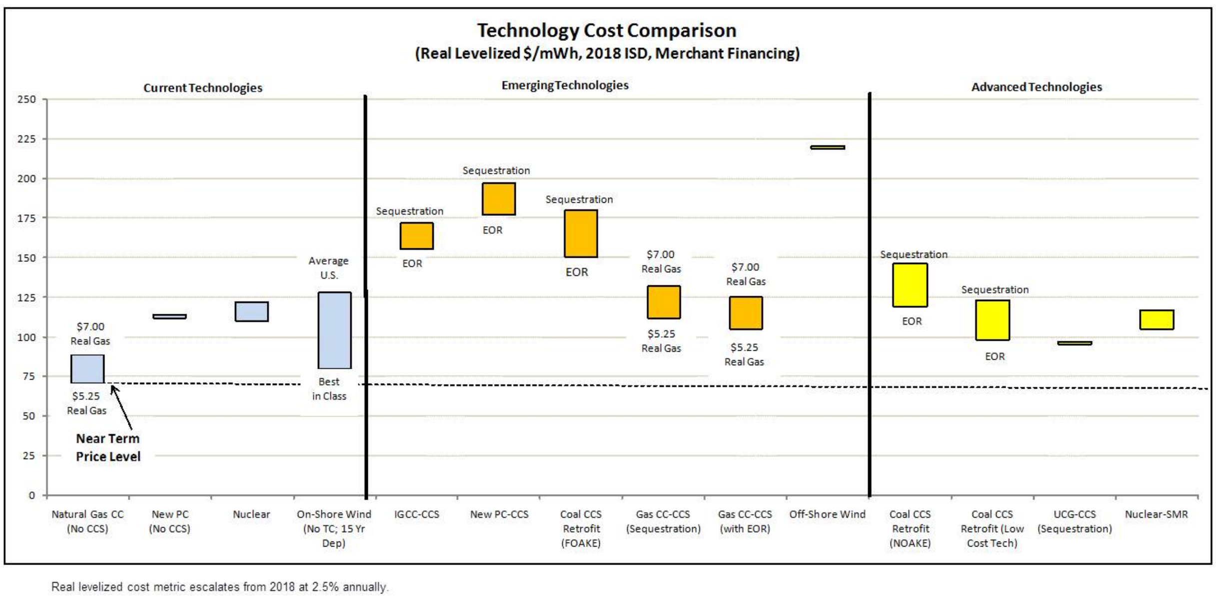

Fig. 10: Comparison for various technologies for electricity generation [133]

CCS help in reducing the total cost for combating climate change by nearly 30% as in the absence of any carbon capture technology, more expensive approach will be needed to help in the reduction of carbon dioxide during energy generation [133]. The total cost of the carbon capture and storage technology is determined by the capturing costs as it accounts for 3/4 of the total cost. It also increases the prices of electricity between 30 - 90% [134]. The main reason for the increase is because there is an energy penalty related with capture and compression of carbon dioxide to make it ready for transport and injection. It should be noted that the cost of electricity prices from an old plant retrofitted with carbon capture and storage technology is cheaper than that of a new plant with carbon capture and storage.

5.1 Gasification challenges

The capture of carbon dioxide from a newly built gasification plant is cheaper than that of a coal plant with post combustion capture [135]. Below are some challenges on gasification.

a) The operational period for an IGCC plant using a gasifier and power production facilities must function at the same time. The gasification and power production are old technologies but integrating them remains a challenge for utilities.
b) The cost of building the facilities for this technology is also a major issue. IGCC in the absence of any carbon capture technology is expensive to build compared to pulverized coal without any carbon capture and storage technology [135]. Due to the challenge in securing the mandate, market price as well as the regulatory framework, recent plants are often designed without any carbon capture and storage.
c) The cost of IGCC plants is also dependent on the altitude and coal type. The higher the altitude, the more expensive to operate

5.2 Post Combustion Capture Challenges.

The main challenges of this CCS type are the high cost and high energy penalties. The electricity produced from traditional coal power plants with post combustion capture is expensive. The levelized cost of electricity is likely to increase to 80% with this type of technology.

a) Retrofit cost for existing plants will be site specific but could approach one half the cost of building a new coal power plant without post combustion capture.
b) There is also high efficiency penalty on coal power plants. The energy needed to heat todays post combustion capture solvents and then compress carbon dioxide from the exhaust stack to pipeline pressure can reduce the output of an existing plant by 30%. These inefficiencies lead to more coal being used for an equivalent amount of electricity sold and this results in increased plants cooling requirements.
c) Incremental improvements in the efficiency and costs of PCC processes are likely following initial commercial-scale demonstrations. Technology developers to date have had little incentive to optimize solvents and process configurations [137].

5.3 Geologic Storage Challenges

Scaling up the technology to address climate change remain a major issue with regards to sequestration. Even though the enhanced oil recovery has been used in recent times on large scale, there are still few sites where large amounts of carbon dioxide have been injected into geologic brine formations [137,138]. More large field demonstration projects are needed worldwide. Science and industry experience strongly indicate that sequestration is safe when practiced in an appropriate site. However, managing hundreds of sources injecting into a single sedimentary basin requires a high level of knowledge sharing and project coordination, as well as research and development support. Monitoring, permitting and long-term care programs must also be developed so that commercial and public sequestration sites can be developed and environmental protection assured. A robust public policy framework must support the development of these institutions [138-140].

6. Conclusion

This paper reviewed the main technologies for carbon capture and storage (CCS) and indicated future prospects of them. The overall goal of the paper is to determine the cheapest capture technology for a specific power plant and other facilities to reduce the emissions of greenhouse gases often considered the major causes of climate change. The paper further described the three current technologies used in carbon dioxide capture including pre combustion, post combustion and oxy combustion. Various types of solvents such as MEA or other amines used for carbon dioxide capture particularly for post combustion were also presented. Other solvents for the capturing of carbon dioxide using chemical solvents were also discussed. The oxy combustion technology was also presented using pure oxygen for the capturing of the carbon dioxide via a chemical process. As explained earlier, the post combustion and the pre combustion are the most accepted technology for capturing of carbon dioxide commercially. These two technologies are also preferred for gas stream purification for various industrial purposes. It is also possible to absorb carbon dioxide from flue gases of several small scale power plant installations but this has not been commercialized. The oxy combustion method of carbon dioxide capture is still going through developmental stages but gradually making predominant strides in the carbon capture and storage industry. The merit and demerit of all the existing technologies for carbon capture and storage were all presented as well. The major challenges that cut across all the three types of technology even though they are capable of high carbon dioxide capture is the fact that the power produced for all technologies are very expensive. Carbon dioxide capture requires large energy and this is one of the reasons for the high cost of technology. For example, almost 15 – 30 percent energy is required per net kWh for new power plants powered by fossil commodities. This is the case for most combustion power plants where there is high energy penalty during the carbon dioxide capture and this increases the overall cost of the system. It must also be noted that renovating carbon dioxide system for existing power plants is more expensive compared to new plants in terms of kWh. Therefore, there is still more work to be done in terms of carbon capture technology for several applications and the future of the world is highly dependent on the pace at which some of these technologies can be commercialized at affordable prices.

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